

National Aeronautics and Space Administration



Space Technology Mission Directorate

ADVANCED PROPULSION STRATEGIC TECHNOLOGY PLAN

INNOVATION & OPPORTUNITY CONFERENCE 2020

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NASA/STMD | HQ

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www.nasa.gov/spacetech

STMD STRATEGIC FRAMEWORK





STMD Strategic Framework

LEAD

THRUSTS

SPACE TECHNOLOGIES





Ensuring American Global Leadership in Space Technology

- · Lunar exploration building to Mars & new discoveries at extreme locations
- Robust national space technology engine to meet national needs
- U.S. economic growth for space industry
- Expanded commercial enterprise in space

Note: Multiple technologies are cross cutting and support multiple thrusts. Primary emphasis is shown.



Rapid, Safe, & Efficient Space Transportation Advanced Propulsion

Precision Landing

Cryogenic Fluid Management



Land

Expanded Access

Destinations

- to Diverse Surface



Live

Sustainable Living and

Working Farther

- from Earth
- Advanced Human Life Support Systems
- Advanced Materials, Structures & Manufacturing

Human & Robotic Entry, Descent and Landing

- Advanced Power
- In-situ Propellant & Consumable Production
- Autonomous Systems & Robotics

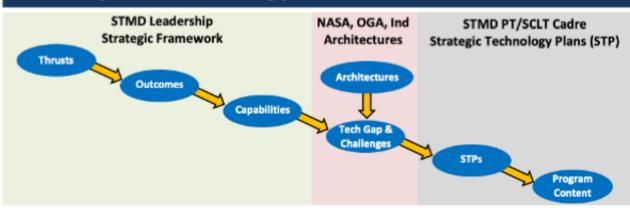


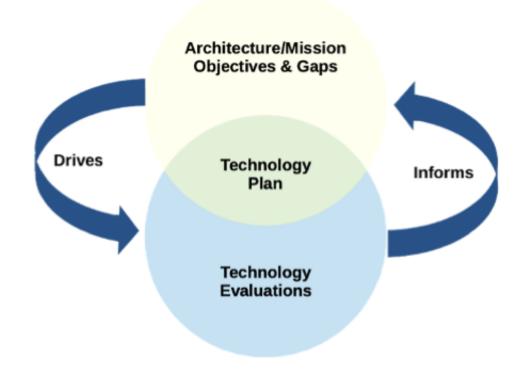
Explore

Transformative Missions and Discoveries

- On-Orbit Servicing, Assembly & Manufacturing
- Advanced Avionics
- Advanced Communications and Navigation
- Extreme Access
- Small Spacecraft Technologies

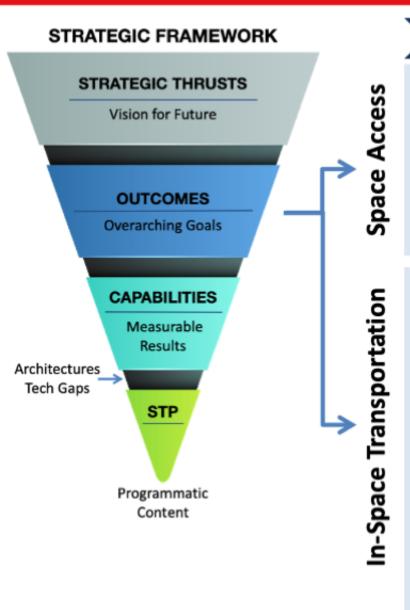
Space Technology Portfolio Formulation





GO THRUST Overarching Strategic Goals





2020s

- Multiple Highly-Reusable Commercial Launch Services (CLV) Fleets Supporting Space Science,
- Multiple Affordable, Dedicated, Responsive Small Launcher Services Fleets for Orbital Delivery of Next Generation Small Spacecraft Platforms

Exploration, Commerce, and Security

- Development of Alternative High-Speed Propulsion Technologies and Integrated Space Access Concepts
- CLV Launch Costs Reduced by Order of Magnitude Supporting Increased Mission Utility & Market Growth

2030s

- Dedicated, Responsive Small Spacecraft Space Access Costs Reduced by 50% Supporting Increased Mission Utility & Market Growth
- Demonstration of Alternative High-Speed Propulsion Systems and Integrated Space Access Concepts

- 2040s Robust Commercially-Sustained Up/Down
- Transportation Market Underpinning a Vibrant and Dynamic Space Economy
- **Establish Routine Commercially-Sustained Airport-**Like Launch Operations with Broad Based User Community
- Introduction of Integrated High-Speed Propulsion Space Access Systems to CLV Fleets

- Introduction of Compact, Reduced-Cost Cold Tolerant In-Space Storable Propulsion Systems for Long-Duration, Extreme Environments Operation
- Accelerated Adoption & Deployment of Reduced-Cost Advanced Manufactured In-Space Cryogenic **Liquid Propulsion Systems**
- Flight Demonstration and Introduction of Mid-Range-Power EP System (7-14 kW Strings) Serving Exploration, Science, Commerce and Security Needs
- Introduction of Rad-Tolerant, High △V, Sub-kW EP Systems Enabling Small S/C Deep Space Missions
- Development & Flight Demonstration of Space Nuclear Propulsion (SNP) Systems (NTP &/or NEP) Establishing Viability, Feasibility, and Affordability
- Sustained Research and Initial Proof-of-Principle Demonstrations of Advanced Energetic Propulsion Technologies to Enable Ambitious Missions Throughout the Solar System & Beyond

- Widespread Adoption and Infusion of Green Propellant Propulsion Systems & Introduction of Rotating Detonation Rocket Engines
- In-Space Cryogenic Liquid Propulsion Costs & Reusability Improved by an Order of Magnitude Promoting Mission Utility & Market Growth
- Flight Demonstration and Introduction of High-Power EP System (50-100 kW Strings) Serving Exploration, Science, Commerce and Security Needs
- Sub-kW EP Propulsion Costs and Lifetime Improved by an Order of Magnitude Promoting Mission Utility
- Flight Certified SNP Systems (NTP &/or NEP) Supporting Fast Opposition-Class Human Expedition to Mars & Outer Solar System kWe-Class Science
- Initial Ground Demonstration of Advanced Energetic Propulsion Technologies to Enable Short Trip Time Interplanetary Missions Throughout the Solar System & Interstellar Flight

- Thrust Scale-Up of Green Propellant Propulsion Systems, Rotating Detonation Rocket Engines, and Advanced Storable Propulsion Systems
- Robust, Highly Reusable Liquid Propulsion Systems Supporting ISRU-Sustained Cis-Lunar/Mars Commercial Fleets
- Introduction of Very-High-Power EP Systems (100 -1000 kW strings) Enabling Efficient & Rapid Cis-Lunar/Mars Transportation of Cargo & Crew
- Widespread Adoption of Sub-kW EP Platforms with Revolutionary Impacts on Mission Capability/Cost
- Robust and Reusable SNP Transportation Systems Supporting Cis-Lunar/Mars Blue Water Mobility and Sustained Mars Exploration
- Initial Breakthrough Flight Demonstration of Advanced Energetic Propulsion Technologies to Enable Short Trip Time Interplanetary Missions and Interstellar Flight

ADVANCED PROPULSION STP





STP – Table of Contents

- Definition & Scope of Technology Domain
- Architecture Drivers
 - Technology Gaps & Challenges
 - Quantifiable Capability Outcomes
- Structured Technology Maturation & Closure Plans
- Transformational Technology Push
- Industry, DOD & OGA Data (Limited Distribution)







Apportionment of Space Propulsion Technologies across STPs*

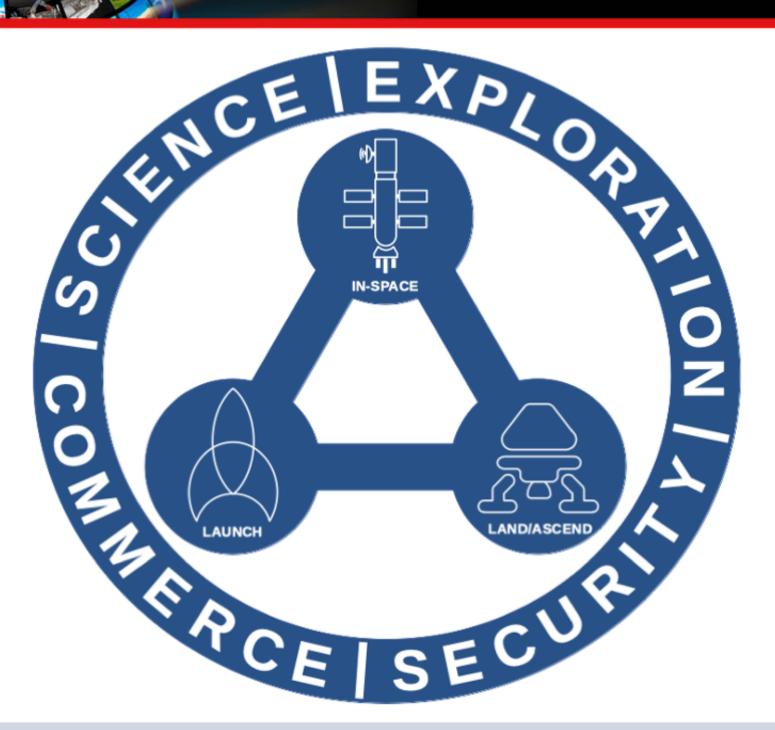
| STP | TX-1 Propulsion Systems | | | | TX-9 EDL |
|---------------------|--|---|--|--|--|
| | 1.1 Chemical Space Propulsion | 1.2 Electric Space Propulsion | 1.3 Airbreathing Propulsion | 1.4 Advanced Propulsion | 9.3 Landing Propulsion |
| Advanced Propulsion | StorableSolidHybrid | Electrostatic Electromagnetic Electrothermal | Space Access TBCCSpace Access RBCC | Sails/TethersNTP/NEPAll Other | StorableSolidHybrid |
| СҒМ | Cryogenics TechnologiesIntegrated CFM Systems | N/A | Cryogenics TechnologiesIntegrated CFM Systems | Cryogenics TechnologiesIntegrated CFM Systems | Cryogenics TechnologiesIntegrated CFM Systems |
| AMSM | Materials & StructuresAM Components | Materials & StructuresAM Components | Materials & StructuresAM Components | Materials & StructuresAM Components | Materials & StructuresAM Components |
| SST | Sub-Newton CP | Sub-kW EP | N/A | SST Sails/Tethers | Small Lander Craft |

^{*} Based on 2020 NASA Technology Taxonomy

ADVANCED PROPULSION DEFINITION & SCOPE

Space Transportation Triad & Advanced Propulsion Technologies





PROPULSION TECHNOLOGY TAXONOMY











CP - Chemical Propulsion

SEP - Solar Electric Propulsion

NEP - Nuclear Electric Propulsion

NTP - Nuclear Thermal Propulsion

NTP

PLP - Propellant-Less Propulsion

AEP - Advanced Energetic Propulsion

CROSS-CUTTING SUPPORT TECHNOLOGIES







AMSM

CFM - Cryogenic Fluid Management AMSM - Advanced Materials, Structures, & Manufacturing P&D - Power & Distribution

SPACE FLIGHT DOMAINS

Science, Exploration, Commerce & Security

Uranus

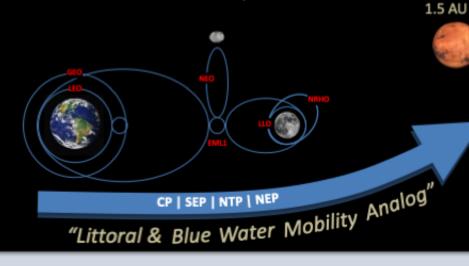


200-400 AU

CIS-LUNAR CLPS/ARTEMIS & CIS-**LUNAR DEVELOPMENT**

- Science Payloads
- Mining & Resource Extraction
- Manufacturing
- Fuel Depots
- Space Solar Power
- Outposts (In-Space & Surface)
- Tourism
- Rule of Law Compliance
- Planetary Defense Assets
- Space National Security Assets

"Commercially Sustained Cis-Lunar Infrastructure" $\Delta v < 5 \text{ km/s}$



MESO-SOLAR MOON-TO-MARS & EXPANDING SCIENCE/EXPLORATION

Humans on Mars

Search for Life

Sample Return

Mars

Outer Planetary Science

Resource Mapping

Asteroid Prospecting

19 AU Saturn "Rapid & Efficient Deep Space Transit" Jupiter 5.2 AU

EXTRA-SOLAR OUTER SOLAR SYSTEM & INTERSTELLAR

KBOs & Primitive Bodies >50 AU

Heliosphere / Local ISM 100-200 AU

Pristine ISM

Solar Gravity Lens 500-800 AU

4.5-20 LY Nearby Stars / Exoplanets

PROPULSION TECHNOLOGY TAXONOMY



Pluto

Neptune

30 AU











CP - Chemical Propulsion SEP - Solar Electric Propulsion **NEP - Nuclear Electric Propulsion**

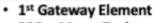
NTP - Nuclear Thermal Propulsion PLP - Propellant-Less Propulsion AEP - Advanced Energetic Propulsion

IOC 2020

EXPLORATION ARCHITECTURE DRIVERS

Lunar Phase





- PPP Maxar Tech
- 50kW-Class SEP
- AEPS Infusion
- ➤ 12.5-kW HET Strings
- ➤ 2000-kg Xe Capacity
- Multi-Phase Demo
- ➤ Launch, Deploy, Checkout
- SEP Orbit Transfer
- ➤ NRHO Demo
- ➤ Handover

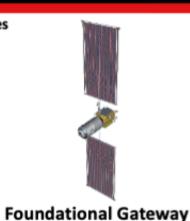
PPE

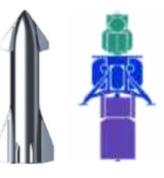


CLPS

Commercial Lunar Payload Services

- Multiple Qualified Providers (14)
- Initial Mission Selections
- ➤ Astrobotic 2021
 - Peregrine (MON-25/MMH)
- ➤ Intuitive Machines 2021
 - Nova-C (LOX/CH4)
- ➤ Masten 2022
 - XL-1 (MXP-351 Proprietary)
- ➤ Astrobotic 2023
- Griffin (MON-3/M20)







Artemis HLS Crew/Cargo Services

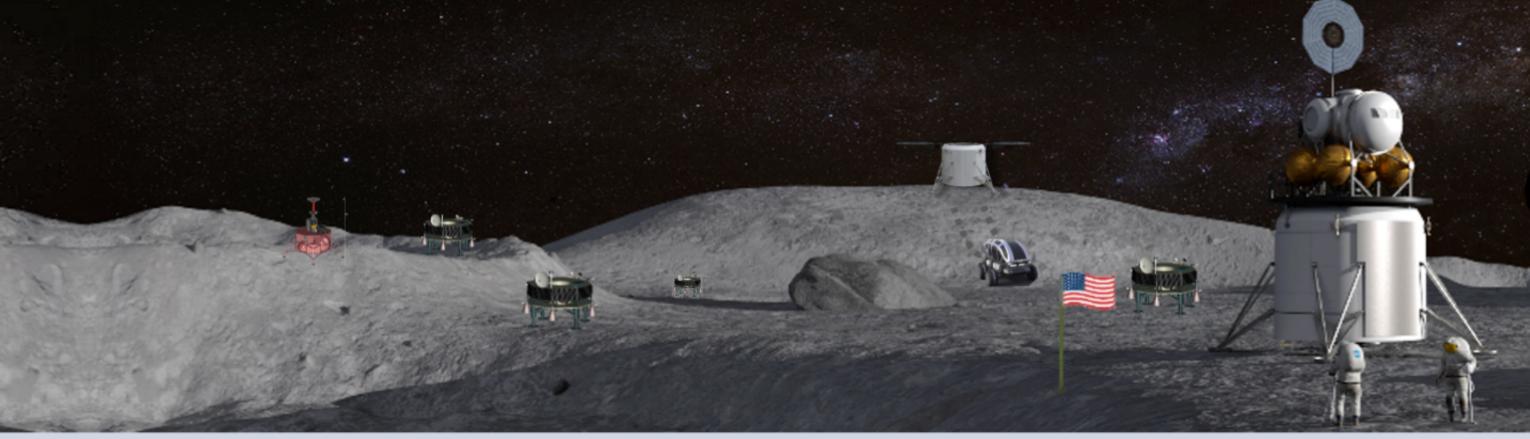
HLS Development Selections

- ➤ SpaceX
 - Starship (LOX/CH4)
- ➤ Blue Origin National Team
 - Transfer NG (LOX/H2)
- Lander BO (LOX/H2)
- Ascent LM (OMS-E Storable)
- Dynatics
- Modular Propellant Vehicles (LOX/CH4)
- ALPACA

Artemis Commercial Crew & Cargo Lunar Surface Access Systems

ISS/LEO Testing | Foundational Gateway Operations | Lunar Surface Precursors

Lunar Surface Human Return





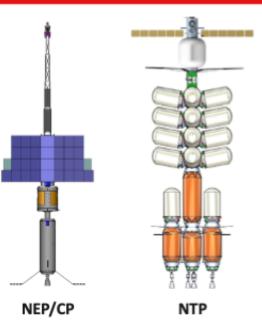
EXPLORATION ARCHITECTURE DRIVERS

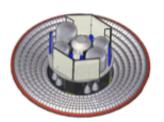
Mars Phase



Mars Transport Options

- NEP/CP Hybrid Current Reference Configuration
- ➤ High Thrust CP Gravity Well ΔV
- ➤ Multi-MW NEP Cruise ΔV
- ➤ LOX/LCH4 Storage/X-Fer
- ➤ Opposition-Class Capability
- NTP Alternate
- > High Thrust NTP Gravity Well ΔV
- > Reactor Integrated OMS Supplemental ΔV
- ➤ LH2 Storage/X-Fer
- > Opposition-Class Capability

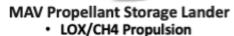




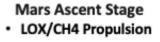
Mars EDL

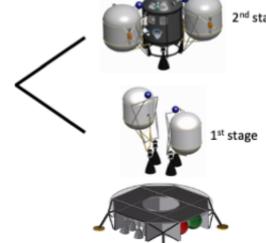
Lander Delivery



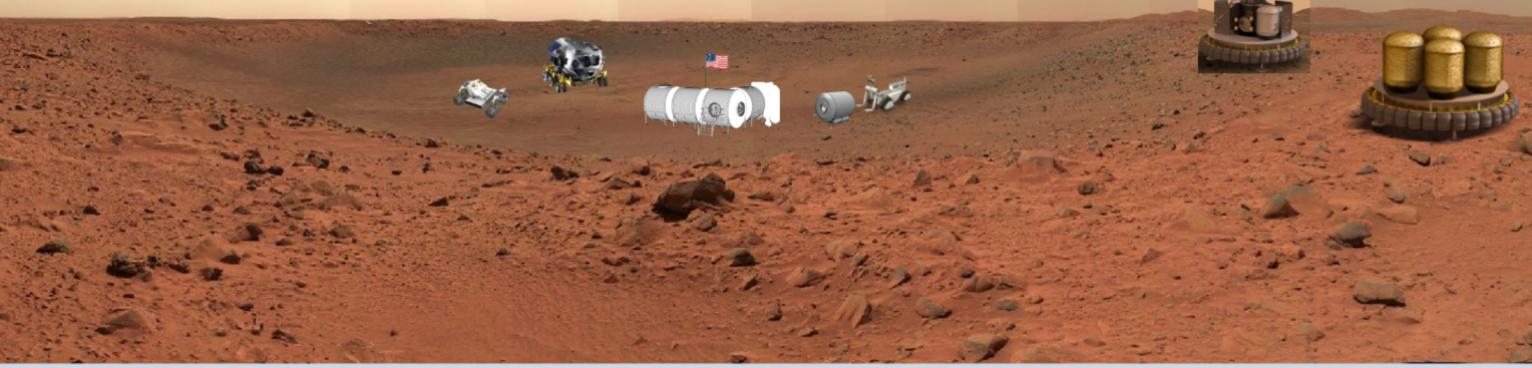








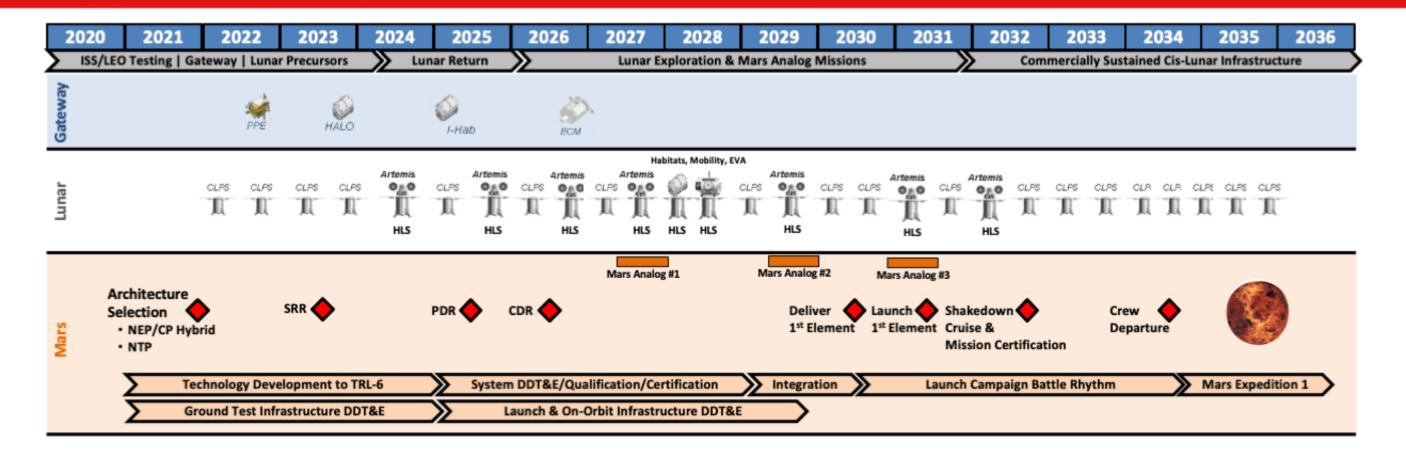
Mars Descent Module



EXPLORATION ARCHITECTURE DRIVERS



Moon-to-Mars Campaign – Transportation Architectures & Elements



MTAS Programmatic Assumptions*

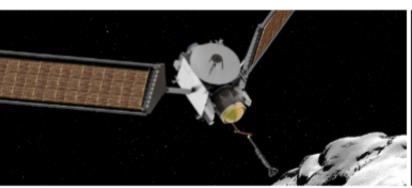
- Component/Subsystem TRL-6 @ Element PDR
- System-Level Ground Test Infrastructure 80% Complete @ Element PDR
- Element PDR Occurs at Least 5-years Prior to 1st Element Launch
- Critical Systems TRL-6 @ Element CDR
- Element Delivered to Range 1-year Prior to Launch

^{*} Vetted by MTAS Programmatic Team

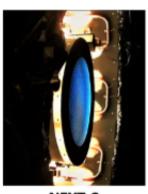
SCIENCE, COMMERCE & SECURITY ARCHITECTURE DRIVERS

Enhanced Spacecraft/Platform Mobility

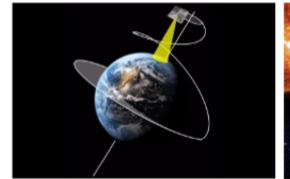




High-ΔV EP Robotic Spacecraft







Earth Pole-Sitting Satellite



Sun Pole Observer Satellite

10-kWe NEP Neptune-Triton Spacecraft

Deep Space Science, Commercial & Security Missions Requiring Very High-ΔV EP Capability Beyond NSTAR

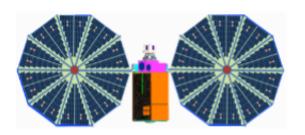
- NEXT-C Xenon Ion Engine
- ➤ Enable Highly Challenging New SEP/NEP Robotic Missions
- ➤ Extend Power, Thrust, Isp, & Xenon Throughput beyond NSTAR
- ➤ Second String NEXT-C Engineering Closeout & Build
- ➤ Demonstrate Full Capabilities & Flight Qualification

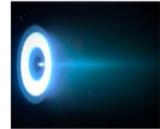
Outer Solar System Science Requiring NEP Capability

- KiloPower Derived 10-kWe NEP
- ➤ Enable High-ΔV Missions Beyond SEP
- ➤ Abundant Deep Space S/C Power
- ➤ Improved SWaP, COMM & Trip Time
- ➤ Leverage Fission Surface Power Dev

Observational Platforms for Science, Commercial & Security Missions Requiring Unlimited ΔV Capability

- Solar Sail Development & Demonstration (e.g., Solar Cruiser)
- ➤ Artificial Equilibria & Indefinite Station Keeping along or offset the SEL
- ➤ Lagrange Point Station Keeping
- ➤ Change Heliocentric Inclination from Ecliptic to Solar Polar
- ➤ Functionally Equivalent Geostationary Earth Orbits





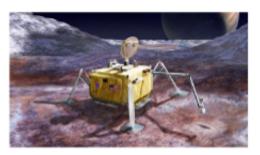


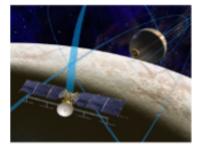
Small Spacecraft Science, Commercial & Security Missions Requiring High ΔV Capability

- Sub-kW Electric Thrusters
- ► Enable High-ΔV SPA-Class S/C Missions
- ➤ Fully Qualify High-Throughput, Rad-Tolerant Capability

Green Propellant Adoption & Infusion into Missions of Opportunity

- Overcome Infusion & Transition Challenges
- Incentivize Mission Adoption
- ➤ PPP to Mature a Wide Range of Thrust Classes





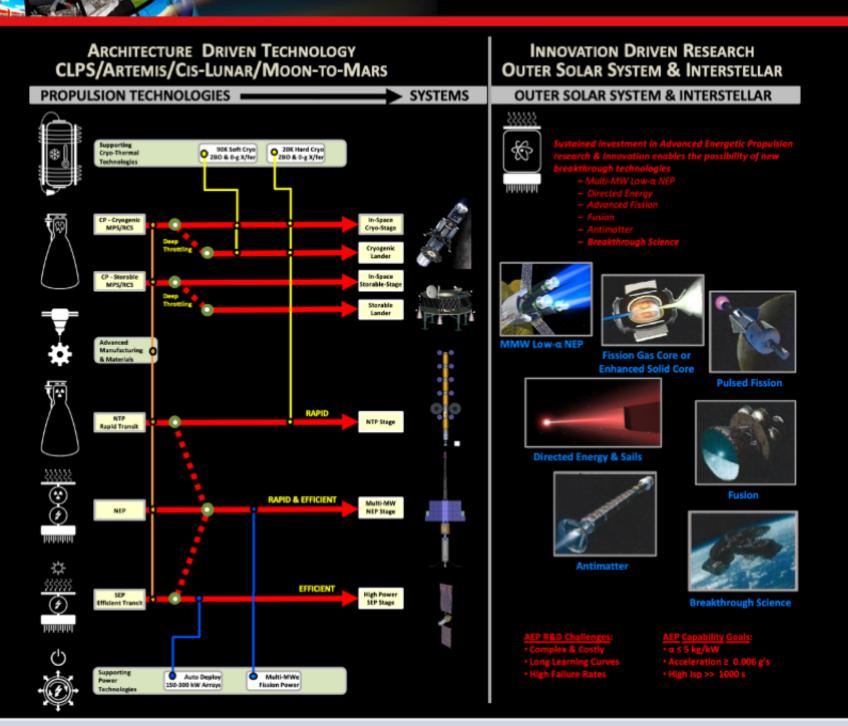
Deep Space Science Missions Requiring Cold Tolerant Storable Propulsion for Extreme Environments Access

- MON-25/MMH Bipropellant Thruster Technology
- ➤ Outer Planetary Body Surface Access Europa Lander
- ➤ Extensible Total Impulse Long Burn Deep Space Orbit Transfer

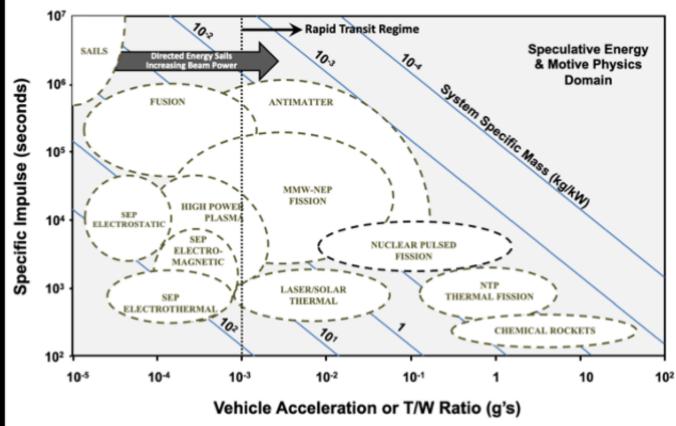
TRANSFORMATIONAL & INNOVATION DRIVEN R&T

Portfolio Diversification & Balance





The Advanced Propulsion Landscape



EXPLORATION ARCHITECTURE GAP INDICES

Quantifiable Capabilities Trace



EXPLORATION

Lunar Phase E1: Gateway

E1-G1: PPE/SEP

High-Power 50-kWe SEP system to provide lunar orbit maneuvering and NRHO station keeping

- 12.5 kW Magnetic Shielded Xe HET EP String
- Multi-String SEP ≈50 kW
- 2-3 ksec Isp & High Throughput
 >10 khr Operability
- Long Life Durability >10 yrs & Mission Use > 1

EXPLORATION

Lunar Phase E2: Artemis/HLS

E2-G1: Cryo Propulsion

Affordable, highly reusable cryogenic propulsion to provide in-space transport and lunar surface access with extensibility to Mars

- 10-15 klbf Cryogenic Liquid Rocket Engines @ Isp ≥ 350 sec
- Integrated Cryogenic MPS/RCS
- Multi-Start Durability (> 300 hrs) & Mission Use > 1
- LOX/LCH4 CFM ZBO
 Storage/X-fer & Low Power @
 90K*
- LH2 CFM ZBO Storage/X-fer & Low Power @ 20K*
- Advanced Manufactured Engine Components†

* Cryogenic Technologies Apportioned to CFM STP

† Advanced Manufacturing Apportioned to AMSM STP

EXPLORATION

Mars Phase

E3: Mars Transport

E3-G1: NEP/CP

Multi-MW NEP to provide cruise ΔV plus affordable & highly reusable cryogenic propulsion to provide gravity well ΔV

 1200-1800 K Fission Power Reactor w/ He/Xe Brayton PCS

- 480 VAC to 650 VDC DD PMAD
- 100 kW EP String
- Multi-String EP ≥1.6 MW
- 2000-3000 sec lsp
- DDU PMAD Efficiency 99%
- 150-200 mg/s Flow Rate
- . High Throughput >10 khr Operability
- Common In-Space & Lander Cryogenic Propulsion
- 10-25 klbf Cryogenic Liquid Rocket Engines @ Isp > 350 sec
- Integrated Cryogenic MPS/RCS
- . Multi-Start Durability > 300 hrs
- LOX/LCH4 CFM ZBO Storage/X-fer & Low Power @ 90K*

E3-G2: NTP

High thrust NTP to provide gravity well ΔV plus reactor integrated OMS to provide supplemental ΔV

- Thrust ≥ 25 klbf (≈500 MW Reactor)
 @ Thrust/Weight > 3
- HALEU Fuel Element ≥ 2850 K @ Isp ≥ 900 sec
- Integrated OMS @ Isp ≥ 500 sec
- ∆V ≥ 10 km/s Enable Opposition & Conjunction Missions
- Fission Product Leakage <
 NERVA/ROVER Milestone
- Total Run Duration ≥ 5 hrs @ Rated Temperature
- Engine Restarts ≥ 10
- LH2 CFM ZBO Storage/X-fer & Low Power @ 20K*



SCIENCE, COMMERCE & SECURITY ARCHITECTURE GAP INDICES

Quantifiable Capabilities Trace



SCIENCE, COMMERCE & SECURITY

S1: Flagship EP

S1-G1: NEXT-C EP
Beyond NSTAR EP capability
to enable more ambitious
very high ΔV SEP/NEP deep
space missions

- 0.5-7 kW Xenon Ion Thruster EP String
- 25-235 mN Thrust @ 1400-4200 sec lsp
- High Throughput > 35 MN-s (≈600 kg Xe)
- Long Life Durability > 15 yrs
- Full Life Ground Qualification & Demonstration of Throughput

<u>& SECURITY</u>
S2: Flagship NEP

S2-G1: 10-kWe NEP
Kilopower* derived nuclear
electric propulsion to
enable challenging outer
planet missions beyond
SEP/RPS capability

- 10 kWe (50 kWth), 800 °C, UMo Fission Core with Reactor Integrated Na Heat Pipes
- 10-kWe Multi-Engine Stirling Power Conversion System with Finned Titanium/Water Heat Pipe Radiators
- Integrated Kilopower/ EP String NEP system design
- NEP System Specific Mass ≤ 100 kg/kW with Lifetime ≥ 15 yrs

SCIENCE, COMMERCE & SECURITY S3: Extreme Access S3-G1: Storable Propulsion S3-G2: Storable Propulsion Baseline TALOS: In-space Extensible TALOS: Design cold tolerant storable pulsemodification & qualification mode bi-propulsion to for high-throughput, longburn deep space orbit enable extreme environment access transfer and extreme access 150-lbf MON-25/MMH 150-lbf MON-25/MMH Bipropellant Engine (MPS) Bipropellant Engine (MPS) 10-lbf MON-25/MMH 10-lbf MON-25/MMH Bipropellant Engine (ACS) Bipropellant Engine (ACS) Reduce Propellant Freezing High Area Ratio Nozzle High Throughput / Long Burn Point < -40 °C Europa Lander Qualification Reduce Propulsion System Mass Thrust Scale-Up: 250-1000 lbf ≥80% Reduce Propulsion System Vol ≥50%

Reduce Propulsion System Cost

 High-MON Fluid Property Characterization & NIST REFPROP Update

≥50%

* KiloPower Technology Apportioned to Advanced Power STP

SCIENCE, COMMERCE & SECURITY ARCHITECTURE GAP INDICES

Quantifiable Capabilities Trace



SCIENCE, COMMERCE &
SECURITY
S4: High ΔV Small S/C*

S4-G1: Sub-kW SEP

High-throughput, radiationtolerant sub-kW Xenon HET to support high ΔV SPAclass deep space missions

- 0.5-1 kW Magnetic Shielded Xe HET EP String
- >50 mN Thrust @ 1500-2000 sec lsp
- Radiation Tolerant
- SPA-Class S/C ΔV > 5 km/s
- High Throughput > 2 MN-s with > 10,000 hrs Lifetime

SCIENCE, COMMERCE & SECURITY S5: Unique Platforms

S5-G1: Solar Sail Dev/Demo
Matured solar sail
technology to provide
essentially unlimited S/C ΔV
as an enabler of unique
platform capabilities

- Deployable Sail Membrane Area > 1600 m²
- Characteristic Acceleration > 0.13 mm/s²
- Deployable Composite TRAC Booms
- Embedded Polyimide Photovoltaics
- Embedded Liquid Crystal Reflective Control Device (LC-RCD)
- CM/CP Offset Control via Active Mass Translator (AMT)

SCIENCE, COMMERCE & SECURITY

S6: Green Transition

S6-G1: Green Propellant
Facilitate green propellant
infusion by incentivizing
mission adoption and PPP
opportunities to mature a
wide range of thrust classes

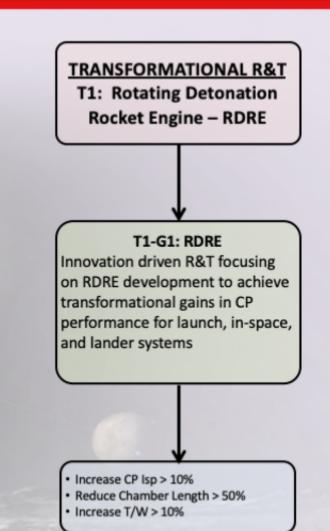
- 1-22 N Green Propellant Propulsion Systems (3-5 yrs)
- Scale-Up: 110 N (5-7 yrs) & 440 N (7-10 yrs)
- Increase Density-Isp ≥ 25%
- Reduce Propellant Freezing Point < -40 °C
- Reduce Thruster Power Consumption ≥ 50%
- Increase Propellant Throughput/Lifetime ≥ 125 kg
- Reduce Ground Operation Costs
 ≥ 50%
- Reduce or Eliminate SCAPE Suit Ops

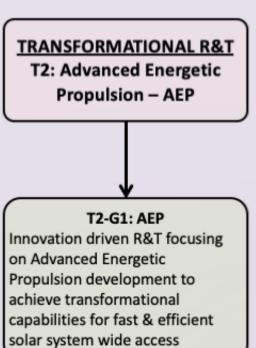
^{*} Sub-kW SEP Apportioned to Small Spacecraft Technologies STP

TRANSFORMATIONAL PUSH TECHNOLOGIES

Quantifiable Capabilities Trace





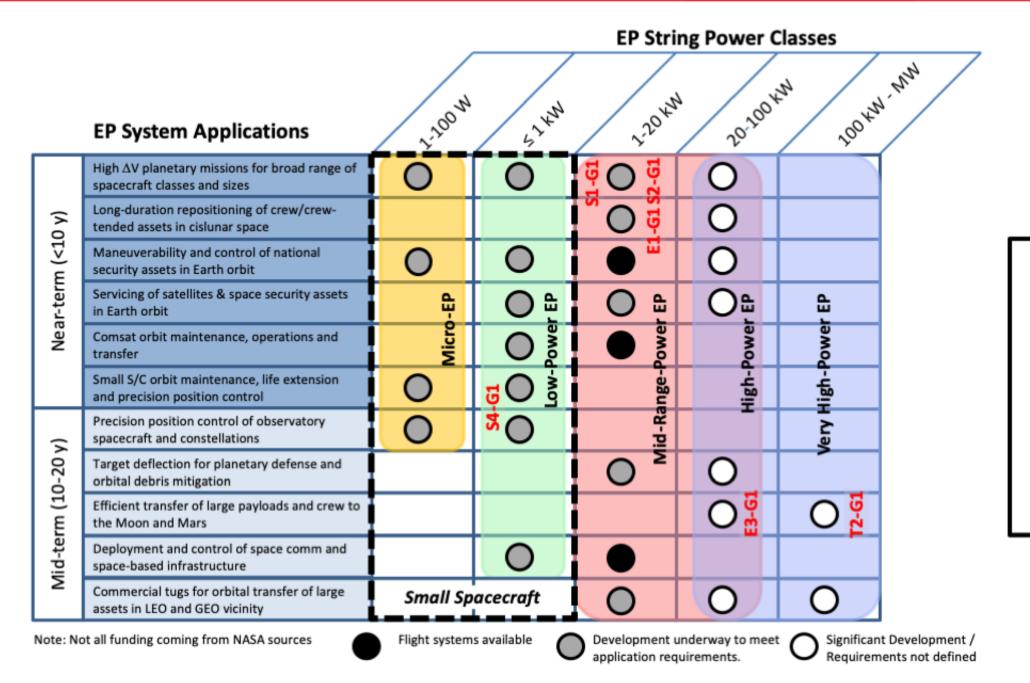


- α_{sys} ≤ 5kg/kW
- Characteristic Acceleration ≥ 0.006 g's
- Isp >> 1000 sec

ELECTRIC PROPULSION SYSTEMS



Historical Developments & Projected Capabilities



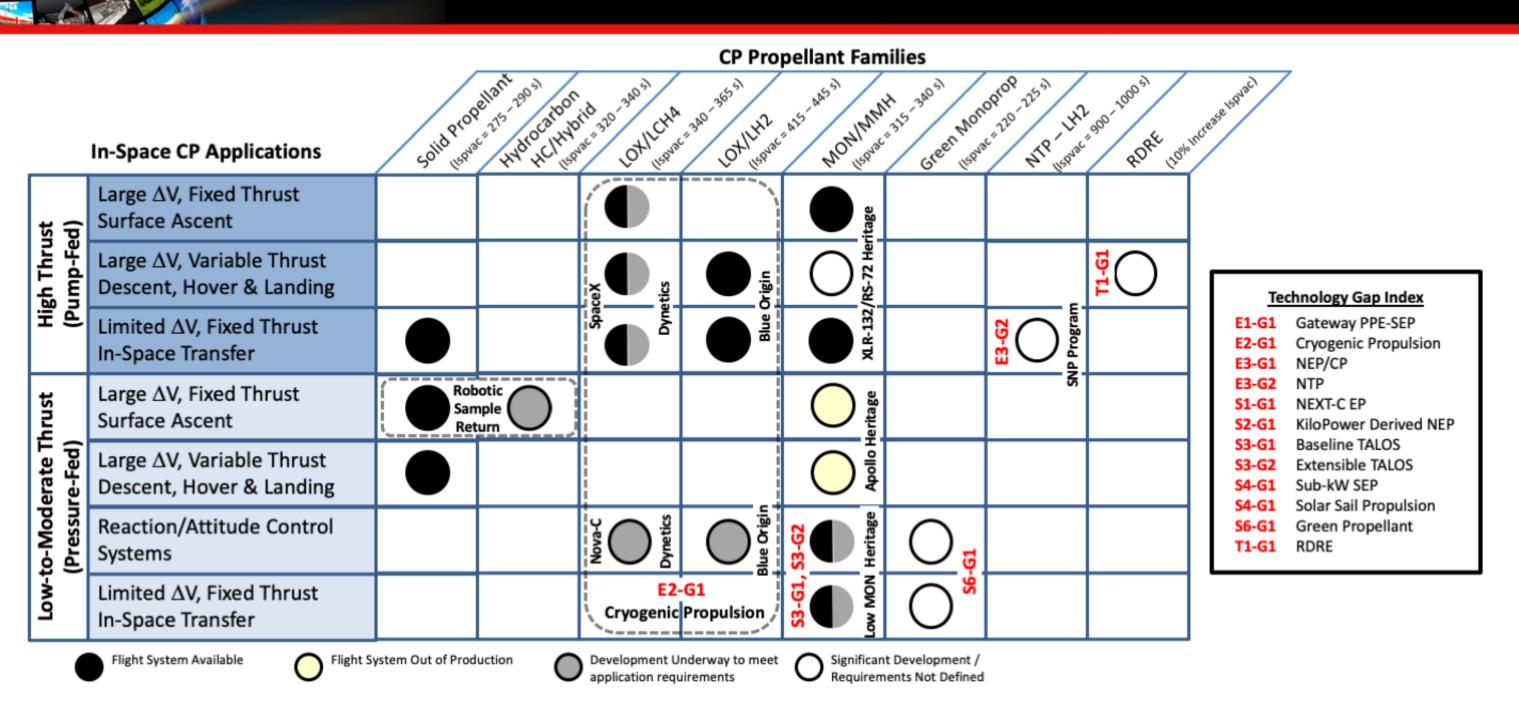
Technology Gap Index

- E1-G1 Gateway PPE-SEP
- E2-G1 Cryogenic Propulsion
- 3-G1 NEP/CP
- E3-G2 NTP
- \$1-G1 NEXT-C EP
- S2-G1 KiloPower Derived NEP
- S3-G1 Baseline TALOS
- S3-G2 Extensible TALOS
- 4-G1 Sub-kW SEP
- S4-G1 Solar Sail Propulsion
- S6-G1 Green Propellant
- T2-G1 AEP

CHEMICAL PROPULSION SYSTEMS



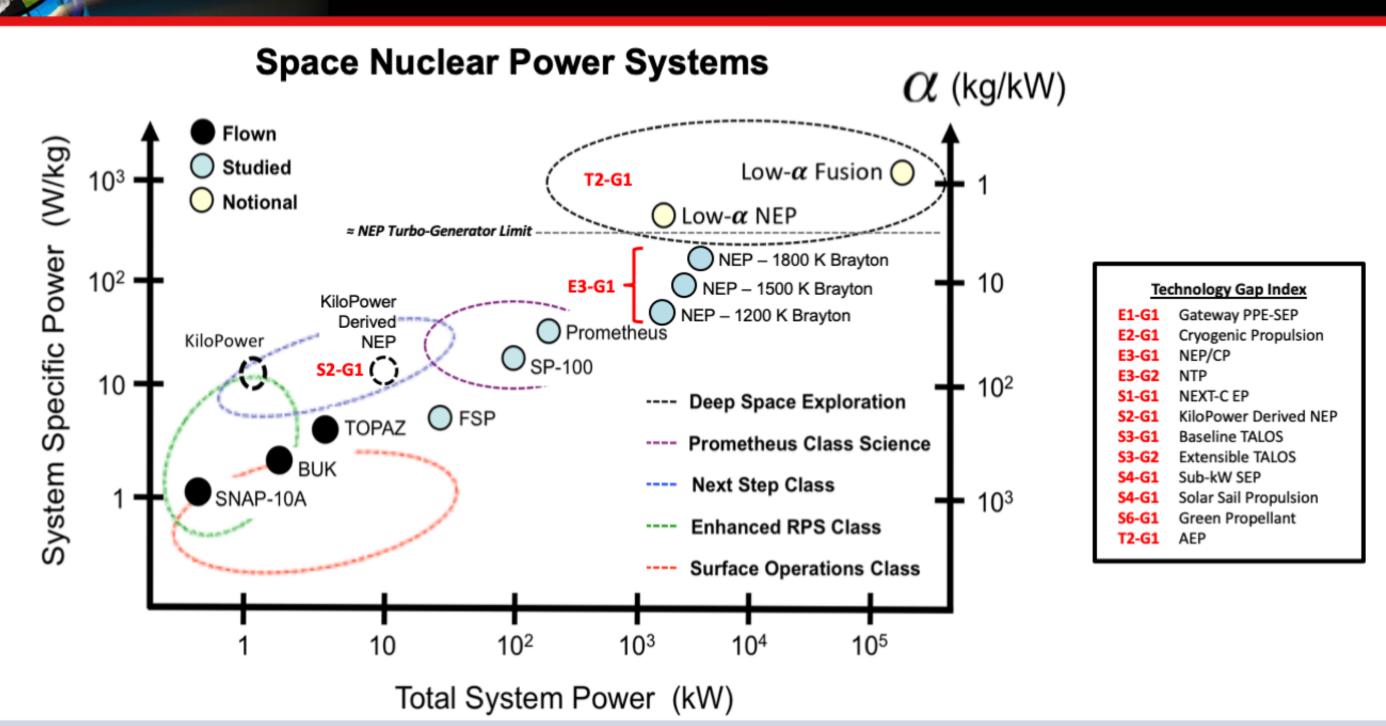
Historical Developments & Projected Capabilities



SPACE FISSION POWER SYSTEMS



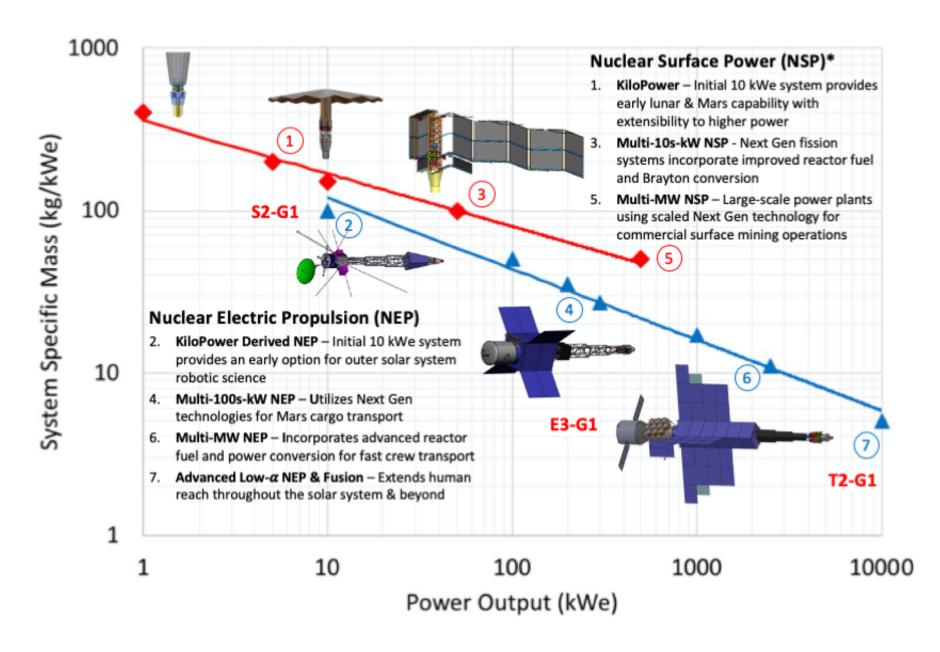
Historical Developments & Projected Capabilities



SPACE FISSION POWER & PROPULSION SYSTEMS

Synergistic Development of NSP & NEP





Technology Gap Index E1-G1 Gateway PPE-SEP Cryogenic Propulsion NEP/CP NTP E3-G2 S1-G1 NEXT-C EP KiloPower Derived NEP Baseline TALOS S3-G1 Extensible TALOS Sub-kW SEP Solar Sail Propulsion **Green Propellant** AEP T2-G1

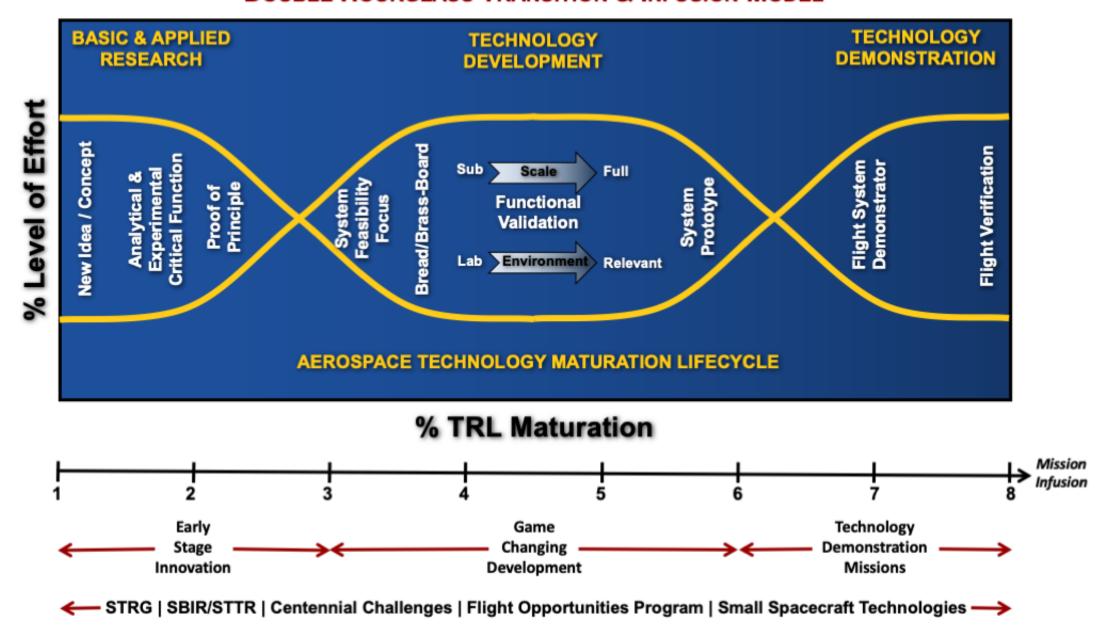
^{*} Apportioned to Advanced Power STP

STRATEGIC CROSS-PROGRAM INTEGRATION



STMD Technology Lifecycle

DOUBLE HOURGLASS TRANSITION & INFUSION MODEL

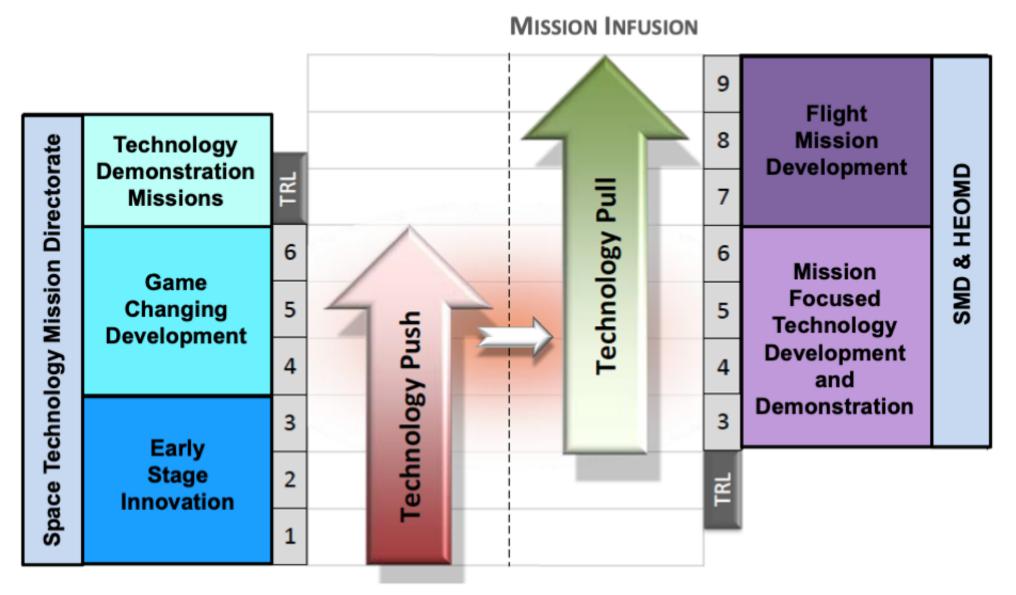


SPACE TECHNOLOGY MISSION DIRECTORATE PROGRAM PORTFOLIO

STRATEGIC CROSS-PROGRAM INTEGRATION



Space Technology Programmatic Flow

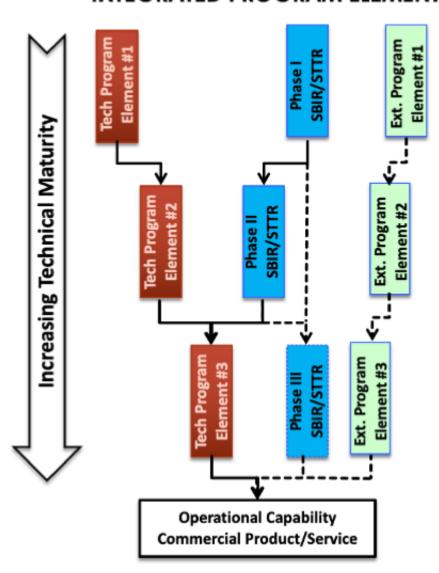


STRATEGIC CROSS-PROGRAM INTEGRATION





INTEGRATED PROGRAM ELEMENTS



CAPABILITY DEVELOPMENT COMMITMENT PARTITION

